

Original research paper

Combined electric and acoustic hearing performance with Zebra[®] speech processor: Speech reception, place, and temporal coding evaluation

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Objective: To assess the auditory performance of Digisonic[®] cochlear implant users with electric stimulation (ES) and electro-acoustic stimulation (EAS) with special attention to the processing of low-frequency temporal fine structure.

Method: Six patients implanted with a Digisonic[®] SP implant and showing low-frequency residual hearing were fitted with the Zebra[®] speech processor providing both electric and acoustic stimulation. Assessment consisted of monosyllabic speech identification tests in quiet and in noise at different presentation levels, and a pitch discrimination task using harmonic and disharmonic intonating complex sounds (Vaerenberg *et al.*, 2011). These tests investigate place and time coding through pitch discrimination. All tasks were performed with ES only and with EAS.

Results: Speech results in noise showed significant improvement with EAS when compared to ES. Whereas EAS did not yield better results in the harmonic intonation test, the improvements in the disharmonic intonation test were remarkable, suggesting better coding of pitch cues requiring phase locking.

Discussion: These results suggest that patients with residual hearing in the low-frequency range still have good phase-locking capacities, allowing them to process fine temporal information. ES relies mainly on place coding but provides poor low-frequency temporal coding, whereas EAS also provides temporal coding in the low-frequency range. Patients with residual phase-locking capacities can make use of these cues.

Keywords: Cochlear implant, Electro-acoustic stimulation, EAS, Temporal fine structure, TFS, Pitch, A&E, Harmonic intonation, Disharmonic intonation, Residual hearing

Introduction

Whereas cochlear implants (CI) may provide good speech understanding in quiet in persons with severe and profound hearing loss, speech understanding in background noise and music listening still remain a challenge for most CI users. This is believed to be at least in part attributable to the current CI limited ability to encode pitch (Gfeller *et al.*, 2007; Fishman *et al.*, 1997). This relates to both impaired frequency selectivity (see Moore, 2007 for a review) and impaired perception of temporal fine structure (TFS) cues (the rapid oscillations with a rate close to the center frequency of the band; Lorenzi *et al.*, 2006; see Moore,

2008 for a review; Hopkins *et al.*, 2008; Lorenzi *et al.*, 2009). The frequency selectivity required for speech perception in noise is finer than for speech understanding in quiet (Fu *et al.*, 1998). Spectral selectivity is tonotopically coded in the cochlea. Most implant users, however, distinguish less than 10 channels of distinct ‘place–frequency’ information across the entire spectral range (Friesen *et al.*, 2001), which does not suffice for good speech understanding in background noise. TFS cues are especially important for speech understanding in fluctuating noise and listening in noise valleys (Lorenzi *et al.*, 2006; Gnansia *et al.*, 2009). In a normal-hearing auditory system, this fast temporal information is mainly coded by phase-locking mechanisms within an auditory channel. TFS cues, however, are not successfully

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transmitted by current CI processors. Even if CI algorithms would improve in temporal pitch coding, it remains questionable whether the CI users would benefit from it, since it has been shown that TFS coding by means of electrical stimulation has an upper limit of 300 Hz (Zeng, 2002).

Recent improvements in CI and soft surgical procedure now allow some preservation of residual acoustic hearing in the low-frequency range (Lenarz, 2009). This is often realized by reducing the electrode array insertion depth, either by a partial insertion (von Ilberg *et al.*, 1999; Gantz and Turner, 2003; Turner *et al.*, 2004), or by using dedicated low-traumatic electrode arrays (Helbig *et al.*, 2008; Lenarz *et al.*, 2009). In these patients, usable acoustic hearing is typically preserved up to frequencies of 500–1000 Hz. This allows acoustical stimulation in the low frequencies while the mid and high frequencies are stimulated electrically by means of the implant. Thus, these patients perceive sound via a combined electro-acoustic stimulation (EAS). It is reported that this combined stimulation improves the subjective sound quality and also the speech recognition in background noise (Turner *et al.*, 2004) as well as pitch perception (Brockmeier *et al.*, 2010).

The assessment of speech understanding in quiet and in noise is common clinical practice, but assessing the coding of TFS cues, related to pitch perception and the underlying phase-locking mechanism, is not. AŞE (Auditory Speech Sound Evaluation; see Daemers *et al.*, 2006; Govaerts *et al.*, 2006; Heeren *et al.*, 2012) is an audiological test suite that includes harmonic intonation (HI) and disharmonic intonation (DI) tests (Vaerenberg *et al.*, 2011) for the assessment of TFS coding.

The goal of the present study is to evaluate the speech understanding in quiet and in noise, and the pitch perception using the HI/DI tests of AŞE in six patients implanted with a Digisonic[®] SP device (Neurelec, Vallauris, France) and a Zebra[®] speech processor providing EAS.

Materials and methods

Patients

Six Digisonic[®] SP (Neurelec) users with preserved residual low-frequency hearing after implantation were identified (Table 1). The median age at implantation was 51 years (range 9–81 years). Until the moment of implant surgery, the subjects used different kinds of high-powered hearing aids that were adequately fitted and maintained. All subjects had residual low-frequency hearing prior to implantation and this was at least in part and unintentionally preserved after implantation with full insertion of the electrodes. Fig. 1 shows the pure-tone thresholds before and after surgery. Post-surgical measures were performed on the EAS testing session day.

Table 1 Individual clinical history

Patient #	Age at implantation (years)	Duration of cochlear implant use (years)	Etiology
1	71	1	Unknown
2	43	2	Progressive
3	81	2	Unknown
4	55	3	Congenital
5	9	5	Congenital
6	45	1	Progressive

The subjects initially received electrical stimulation (ES) only with the Digi SP processor which was programmed according to routine techniques, covering frequencies from 195 to 8008 Hz. Table 1 indicates ES use duration for each patient.

As soon as Neurelec was able to provide EAS by means of the new Zebra[®] processor, the subjects received additional acoustical amplification through an acoustic receiver in an individual ear mould. The median period of ‘ES only’ was 2 years (range 2–4 years). Included patients had no experience of EAS stimulation prior to testing. Written informed consent was obtained from all patients.

Device

The Zebra[®] processor is a CI speech processor, integrating an acoustic output (see Fig. 2). It is compatible with the Neurelec Digisonic[®] SP CI. Its shape is the same as the standard Digi SP and Saphyr[®] SP speech processors. The electrical signal is transmitted through a coil and magnet, as for all CI, and the acoustical signal through a Sonion (Roskilde, Denmark) canal receiver. The computation of both the electric and acoustic signals is performed in the same chipset: the incoming signal is analyzed in several frequency bands (fast Fourier transform (FFT) analysis generating 64 frequency bands, linearly spaced between 190 and 8200 Hz), and all these bands are routed to the input of the electrical and acoustical processing software. This guarantees equality and synchronization of the acoustical and electrical input samples.

The coding strategy for electrical stimulation is MPIS (Main Peaks Interleaved Sampling; see Di Lella *et al.*, 2009; Lazard *et al.*, 2010) as used in the classical Digisonic[®] SP implant with the Digi SP processor. This strategy is based on spectral multi-peak extraction, and interleaved stimulation. The number of transmitted peaks is a parameter that may be modified (default setting: 10 transmitted peaks out of 20 extracted peaks). Loudness coding is realized by varying pulse duration, and pulse amplitude remains constant over time (amplitude set at fitting). The stimulation rate may be set between 260 and 1000 pps per electrode. The default factory setting is 600 pps per electrode.

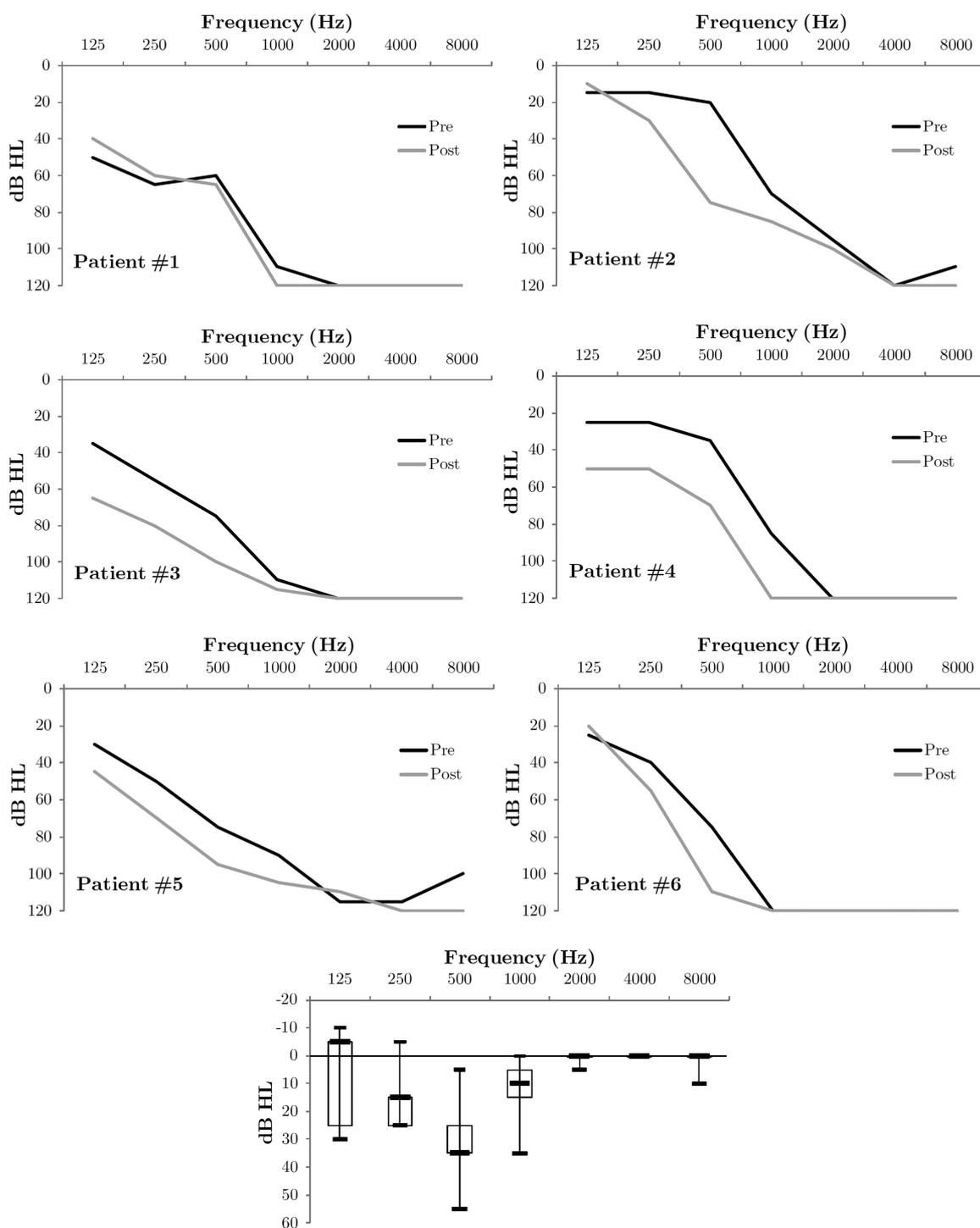


Figure 1 Individual pure tone thresholds before (pre) and after surgery (post). Pre- and post-operative hearing threshold differences are indicated in the bottom figure boxplots showing median values, quartiles, and ranges.

For the acoustical stimulation, all 64 frequency bands from 190 to 8200 Hz are processed, and gains from 0 to 42 dB can be applied for each band separately with a single-band compression of which the parameters (compression rate, attack time, and release time) are set in the fitting software.

Fitting

For the fitting of the acoustical gain, the half-gain rule was applied to determine the necessary amount of acoustic gain, in order to obtain aided thresholds of

about 30 dB HL. However, because of the acoustic power limit of the speech processor and also to avoid distortions due to overamplification, the acoustical amplification applied was 30 dB at all frequencies between 195 and 8008 Hz, except for subject S2, who received 30 dB amplification from 195 to 719 Hz, tapering down to nil between 716 and 1572 Hz.

Outcome measures

All six patients underwent audiological testing, both in the ES and the EAS stimulation modes. Pure tone



Figure 2 The Neurelec Zebra[®] speech processor.

thresholds were performed pre- and postoperatively. This was carried out in a sound treated audiometric room using a Madsen Aurical system (GN Otometrics, Taastrup, Denmark) with free-field loudspeaker outputs calibrated to dB hearing level. The loudspeaker was positioned at 0° azimuth, 1 m from the subject's head. Thresholds to warble tones at octave frequencies between 125 and 8000 Hz were recorded using standard clinical audiometric methods.

Speech audiometry in quiet was performed with open set monosyllabic CVC words (NVA lists; Wouters *et al.*, 1995), presented at 40, 55, 70, and 85 dB sound pressure levels (SPL), using the same room and equipment as above. Two lists of 12 words were used at each intensity level and phoneme scores were recorded. For speech audiometry in noise, open set monosyllabic CVC words (Brugse-lists, Damman, 1990) were presented at 10, 5, 0, and -5 dB signal-to-noise ratio (SNR) with speech-shaped noise at 65 dB SPL. One list of 17 words was used at each SNR and phoneme scores were recorded.

The coding of low-frequency TFS was assessed using the HI and DI tests of A $\mathcal{S}\mathcal{E}$ (Govaerts *et al.*, 2006). The details of these tests and normative data are described elsewhere (Vaerenberg *et al.*, 2011). Briefly, both tests use low-frequency harmonic complexes to find the just noticeable difference (JND, also called difference limen or threshold) for pitch discrimination in individual subjects. In each trial of both the HI and DI test, two stimuli are presented consecutively, one of which contains an intonation, while the other one does not. The test is a same-different discrimination task. The non-intonating stimulus is a harmonic complex signal having a fundamental frequency

(F_0) of 200 Hz and three higher harmonics (with frequencies of $2F_0$, $3F_0$, and $4F_0$). The intensities of the harmonics decrease in comparison with F_0 (-6 dB at $2F_0$, -12 dB at $3F_0$, and -18 dB at $4F_0$). Both in HI and DI tests, this non-intonating sound is presented in contrast to an intonating sound. The intonating sounds used in the HI test feature a frequency sweep of all harmonics (including F_0) from NF_0 to $N(F_0 + \Delta F)$, with $N = 1, 2, 3,$ and 4 respectively. In the DI test, however, the intonating sounds feature a sweep of the fundamental frequency only (F_0 to $F_0 + \Delta F$), whereas the higher harmonics are kept fixed at their initial frequency. As a consequence the harmonic separation of partial tones is distorted by the sweep, hence a disharmonic (or dissonant) intonation. A JND is sought using an adaptive staircase procedure (Vaerenberg *et al.*, 2011). In the current study HI and DI tests were performed using an audio cable connected to the auxiliary input of the processor to deliver the stimuli directly to the implant.

Data analysis and statistical methods

Because of the limited number of included patients, non-parametric statistics were used for all variables. Box-and-Whisker plots are used for graphical representation. Wilcoxon tests for paired samples were conducted to compare the audiological results obtained with EAS to those obtained with ES. The cut-off level for statistical significance was set at 0.05.

Results

Speech perception in quiet

The phoneme scores for speech in quiet are presented in Fig. 3. Gains between the two stimulation conditions in terms of intelligibility for each patient are also presented. In ES mode, the median phoneme scores ranged from 20 to 55% for presentation levels between 40 and 85 dB SPL. In EAS mode, patients showed correct identification of 27–63% of phonemes for the same presentation levels. Gains within patients between the two stimulation modes are shown in Fig. 3B with median values ranging from 8 to 16%. None of the differences were statistically significant.

Speech perception in noise

Results for speech perception in noise in ES and EAS modes are shown in Fig. 4. Patients had median scores between 27 and 51% in ES mode, and between 27 and 59% in EAS, for SNRs between -5 and 10 dB. Median gains between the two stimulation modes were about 10% for all SNRs. Significant differences between the two stimulation modes were found at 10 dB SNR ($P < 0.05$).

HI and DI tests

JNDs from HI and DI tests in ES and in EAS conditions are shown in Fig. 5; standard scores obtained

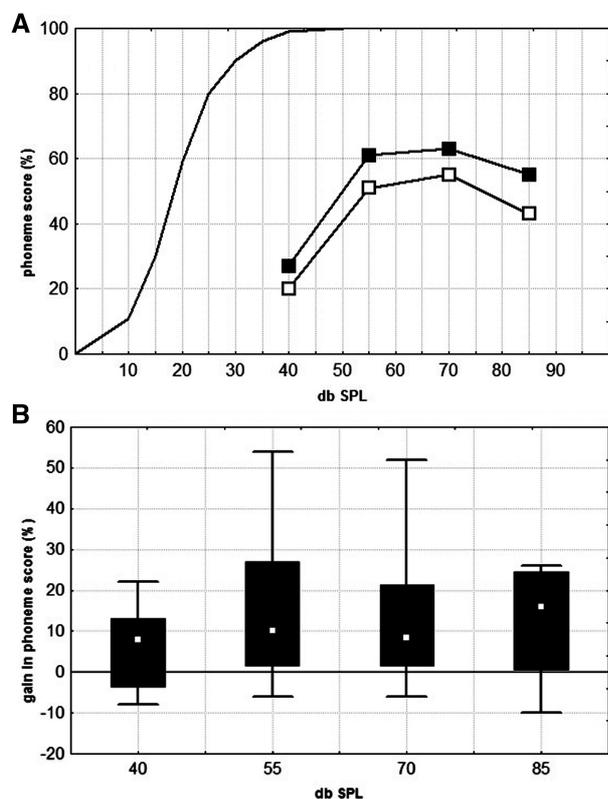


Figure 3 Monosyllabic speech audiometry in quiet. (A) Median phoneme scores at different presentation levels, in electric-only (E, white squares) and electro-acoustic (EA, black squares) conditions. The solid curve depicts normal-hearing performance. (B) Box and whisker plots showing the intra-individual differences between electric-only and electro-acoustic conditions (EA and E). Central point: median; box: lower to upper quartile; whiskers: lower to upper range.

on hearing listeners are also given in the same plot. Gains between ES and EAS are also presented. For HI tests, JNDs measured were similar in ES and EAS, with the median value around 7 Hz. For DI tests, median values for JNDs were 44 Hz in electric-only mode and 12 Hz in electro-acoustic mode. Median values for gains between the two listening conditions were 0 Hz for the HI test and 24 Hz for the DI test. Comparing the two listening conditions, statistical analyses revealed that JNDs for the HI and DI tests were not significantly different (HI: $P = 0.42$; DI: $P = 0.08$).

Discussion

Hearing preservation

Cochlear implantation for patients with residual hearing has never been evaluated with the Digisonic[®] SP implant. The current study has investigated results in Digisonic[®] CI users in whom the hearing was preserved unintentionally. Several studies have investigated hearing preservation using Med-EI CI (C40+ with flex EAS or medium electrode) with ‘long’ electrode arrays and a soft surgery approach. For example Gstoettner *et al.* (2008)

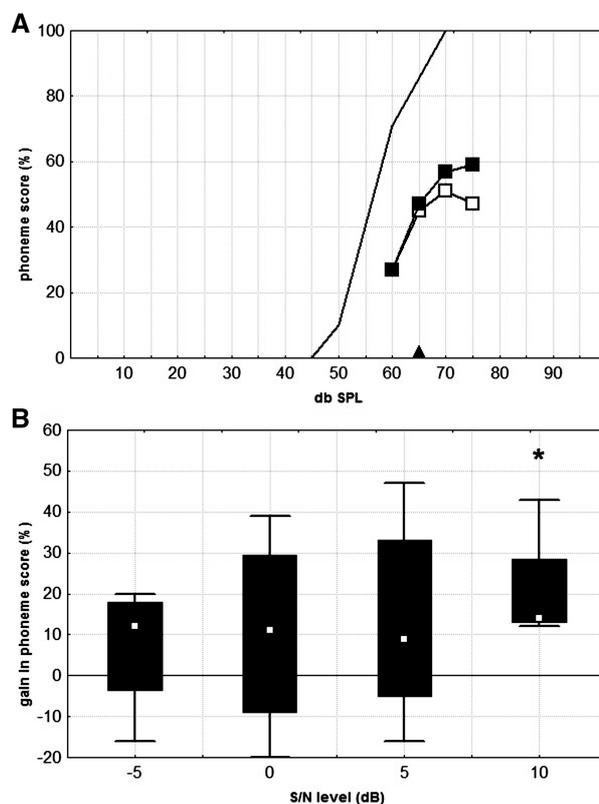


Figure 4 Monosyllabic speech audiometry in noise (65 dB SPL noise). (A) Median phoneme scores at different presentation levels, in electric-only (E, white squares) and electro-acoustic (EA, black squares) conditions. The solid curve depicts normal-hearing performance. (B) Box and whisker plots showing the intra-individual differences between electric-only and electro-acoustic conditions (EA and E). Asterisk: significant with $P < 0.05$.

reported hearing to be preserved in 12 out of 18 patients with average threshold deteriorations ranging from 10 to 30 dB HL. In Gstoettner *et al.* (2009), it ranged from 10 to 25 dB HL in eight out of nine patients. Kiefer *et al.* (2001) reported that at least partial preservation of hearing was accomplished in 11 out of 13 patients, and the mean threshold change for those 11 patients was approximately 15 dB at the lower frequencies, while the remaining 2 patients suffered essentially total losses. James *et al.* (2006) reported a 25 dB loss in the lower frequencies for 12 patients implanted with a long electrode, including the data for two patients who suffered total losses. With the Nucleus CI with Hybrid L electrode-array, Lenarz *et al.* (2009) reported median losses ranging from 10 to 15 dB HL in the low-frequency range.

The current results suggest that hearing can be preserved with the standard Digisonic[®] SP implant with mean hearing loss induced by surgery ranging from 10 to 30 dB HL in the lower frequencies. This degree of hearing preservation seemed comparable with other devices. As said, this hearing preservation was unintentional and only occurred in a minority of cases.

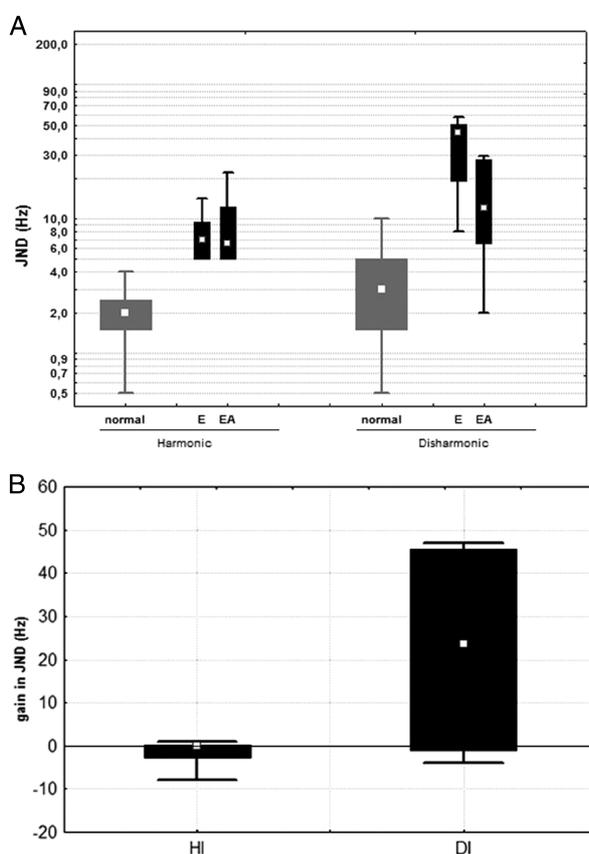


Figure 5 AŞE pitch discrimination test results. (A) Box and whisker plots showing the JNDs (Hz) on harmonic and disharmonic tests, for hearing listeners and implanted subjects in electric-only (E) and electro-acoustic (EA) conditions. (B) Box and whisker plots showing the intra-individual differences between electric-only and electro-acoustic conditions (EA and E).

Speech performance in quiet and in noise

The results of this study indicate an advantage of combined EAS compared to ES for speech understanding in quiet and in noise, which was statistically significant at 10 dB SNR. These results are consistent with those reported by others. For example, Kiefer *et al.* (2001) performed speech recognition tests with monosyllabic words in quiet at 70 dB SPL in patients implanted with other EAS implants (Med-El, Combi 40/40+ and TEMPO+ processor). They reported a mean score of 54% with ES and 62% with EAS (compared to 50 and 64% in the present study using Digisonic[®] SP implant and Zebra[®] processor). Consistent with the present results, their differences were not statistically significant. Using another device from the same manufacturer (Med-El PulsarCI100, Vienna, Austria) in similar test conditions, Prentiss *et al.* (2010) found 38% correct identification in quiet for monosyllabic word identification with ES, and 47% EAS, with no statistical difference between these two conditions.

None of the previous studies on EAS performed monosyllabic word or phoneme recognition in noise in CI users as in the present study. However, speech identification in noise using sentences was always

found to be significantly better with EAS, for SNRs at +5 or +10 dB (Gantz *et al.*, 2006; James *et al.*, 2006; Dorman *et al.*, 2008; Gstöettner *et al.*, 2009; Prentiss *et al.*, 2010). In the present study, identification of monosyllabic words in noise was performed and a significant difference between EAS and ES was observed for 10 dB SNR, which is consistent with the other studies.

HI and DI tests results

There was no statistically significant difference between ES and EAS on the HI test. Both with EAS and with ES only, the performance was poorer compared to hearing subjects and consistent with larger data sets on CI users with different devices (Eargroup, unpublished results). Nevertheless, the HI results are still fairly good, demonstrating reasonable pitch discrimination abilities in CI users when high-frequency cues are available in the complex signal.

One could argue that both temporal envelope and TFS cues may have contributed to the pitch perception in some parts of the tests. However, we believe this to be very unlikely. Both HI and DI signals were constructed to feature temporal envelopes that are stable in time, except for the 30 ms linear fade-in and fade-out, but these are identical for all stimuli. Stimulus envelopes by means of Hilbert transforms did not suggest any available cues in the envelope. There is some variation in the envelope due to the added white noise in the stimuli, but this is totally random and should therefore be unusable as a cue. It should be noted that temporal envelope cues may result from beating when the fundamental frequency in the DI stimulus approaches the 400 Hz harmonic. This effect has been described by Vaerenberg *et al.* (2011) and comes into play only at rather high delta f (>130 Hz (70 Hz beating) for normal-hearing subjects and >60 Hz in CI users (140 Hz beating; Shannon, 1992)). In the current study, the improved pitch perception is unlikely to be attributed to this phenomenon because all subjects obtain JNDs smaller than 60 Hz in all conditions and even below 30 Hz in the EAS condition.

Also loudness cues are unlikely to have played a role in the patient's abilities to discriminate the sounds, even when taking into consideration the fairly steep slopes in some unaided audiograms. The pitch perception was always assessed in the aided condition (either ES or EAS). Audiograms were recorded from all subjects in three aided conditions: ES only, AS only, and EAS. In ES and EAS modes the audiograms were flat (± 10 dB) over all frequencies for all listeners. If subjects were able to use loudness cues to obtain better results in EAS mode then they would originate from the acoustic stimulation, because electric maps were identical in both ES and EAS conditions. However,

for the DI test, the relevant frequency range to explain the observed JNDs is 200 to 250 Hz and audiograms obtained with AS only showed an average absolute difference between the thresholds at 125 and 250 Hz of 7.5 dB. The maximum difference between these thresholds, observed in S5, was 20 dB. S5, however, showed no improvement by adding acoustic stimulation. For the other subjects it is also hard to imagine that they could have extracted a loudness cue from a sweep of around 10 Hz of the fundamental frequency, because the difference in absolute thresholds in the range of this sweep is likely to be less than a decibel. Therefore, we believe it is reasonable to assume that all frequencies in the stimuli caused an equivalent loudness percept and the subject used pitch as a cue rather than loudness.

It might be interesting to consider the possibility that frequencies moved between electrodes as the stimulus changed. All maps used during the study featured a linear spacing of frequencies in the range 195–977 Hz over the six most apical electrodes, yielding a band width of 130 Hz per electrode and an upper cutoff frequency of 326 Hz for the most apical channel. In the DI test only $\Delta F > 125$ Hz should cause activation of the second electrode. All subjects have considerably lower JNDs, which makes us believe that place coded pitch by electrical stimulation is unlikely. However, when considering the possibility of spectral leakage by the FFT into adjacent channels, it could well be that some subjects were able to extract cues from the subtle increase/decrease of cross-channel leakage when frequencies shift up/down. This might explain why some subjects obtain JNDs as low as 8 Hz on the DI test using ES only.

In the HI test the 800 Hz harmonic ($4F_0$) would move to the next channel for a ΔF as low as 12 Hz, resulting in a possible place cue for JNDs recorded above this ΔF . As ΔF becomes larger, more harmonics move to a next channel ($2F_0$ at 28 Hz, $3F_0$ at 39 Hz, $4F_0$ again at 45 Hz, etc.). It is evident that the larger ΔF results in the more salient place pitch cue in the HI test.

The signal processing by the Zebra[®] processor uses an 8 ms window as input for its FFT. When the MPIS strategy maps the amplitude spectrum to electrode activation the phase spectrum is lost. Therefore we assume that it is unlikely to have a temporal pitch cue within one channel. But as for the spectral leakage that may have caused subtle place cues, we cannot entirely exclude that temporal cues may have originated from small fluctuations in the channel's current level that result from artifacts of the signal processing in response to the shifting frequency (e.g. the segmentation of the signal in frames may cause a temporal modulation on the current level if the frame length is not aligned with the input signal's periodicity

and the effect of the applied window is not able to compensate for this). This phenomenon may also have contributed to some subjects' small JNDs observed in the DI test with ES only.

One may disagree with the above reasoning and argue that these small JNDs obtained with ES only indicate the DI test itself to be invalid. However, although we acknowledge the theoretical grounds on which such doubts are based, we believe they are unlikely to explain the above-mentioned observations for reasons given before in this and previous papers.

As for the acoustical part of the stimulation, we find it very reasonable to believe that at moderate ΔF s (<30 Hz), the subjects would have trouble extracting a place pitch cue, especially when considering their hearing losses and the resulting broadening of auditory filters. It seems more reasonable to us to attribute the gain resulting from adding acoustical stimulation, to a temporal pitch cue. For the acoustical processing, the Zebra[®] processor uses the phase spectrum in its inverse FFT, after applying gains to the amplitude spectrum, such that TFS is restored in the acoustical output of the system, allowing for temporal pitch cues (and thus phase locking) in the processing of the acoustical signal by the subject's auditory system.

We believe it is an important finding that EAS improved the DI test results substantially in patients #1, 2, 4, and 6 (Table 2). The group results were not significant though, which may be explained by the fact that patients #3 and 5 already showed good results with ES, which could not be improved by EAS. It is remarkable that DI results in all EAS users in this study are within or near the results obtained in hearing subjects. It is assumed that the DI test assesses the patient's phase-locking capacity, whereas HI may benefit from both phase locking and place coding (Vaerenberg *et al.*, 2011). This is because the DI test only provides low-frequency TFS cues whereas the HI test provides both low- and high-frequency cues. Taken together, these results suggest that electric and acoustic stimulation may provide complimentary information. Certainly ES is used for place coding, yielding fairly good results (but still poorer than in hearing subjects). Acoustic stimulation may provide low-frequency TFS that will

Table 2 Individual HI and DI test results (JND in Hz)

Patient #	Electric-only		Electro-acoustic	
	HI	DI	HI	DI
1	8	57	9	10
2	7	41	7	14
3	7	23	6	27
4	5	47	5	2
5	5	8	5	8
6	14	49	22	29

be processed by the remaining phase-locking capacities in case of residual low-frequency hearing. The present study tends to confirm the effect first discussed in the study by Turner *et al.* (2004), in which the authors found release from masking between steady and fluctuating noise for EAS when compared to ES, which they interpreted as suggestive for better TFS processing with EAS.

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